PROSPECTS FOR MAPPING CANOPY STRUCTURE USING GEOMETRIC-OPTICAL MODELS

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ABSTRACT

Using image models and image processing to establish the structure of forests and woodlands is a valuable goal as the role of structure in the evolution and state of land surfaces becomes more widely recognised. This paper describes work over a number of years which has exploited the interactions between structure and image variance as well as structure and the way image radiance varies with sun and view directions. The applicability of these methods in Australian woodland vegetation is being tested at sites near Canberra and Dubbo. Satellite data, airborne scanner data and wide angle aerial photography have all been collated as well as extensive ground based cover and structure data. In common with findings elsewhere, it has been found that variance based methods are currently difficult to use operationally to map structure parameters such as tree size but that the variations in radiance with sun and view directions (the BRDF) contain key structural information in the form of scale-free ratios such as that of tree height to crown diameter. Current research aims to combine the benefits of the two approaches into one using the directional variation in image variance (the BRVF) to monitor the structure of Australian open forests and woodlands.

INTRODUCTION

High local spatial variance and large, anisotropic change of observed radiance with sun position and sensor view angle are characteristic of images of woodlands and open forest areas. In these ecosystems, the canopy is discontinuous, or `gappy', and the local spatial and view angle variation in images is created by interactions between the discrete nature of the canopy, the high natural spatial variation in canopy structure and the visible shadowing effects these factors create as the sun and view positions vary. Since the magnitude of the shadowing effect in an image is determined by the structure of the cover and the sun and view angles, considerable image variation can be obtained even for an apparently `uniform' cover type when it is viewed at different times and/or from different view positions. The work reported here addresses how this variation might be used to measure the `gappiness' and ecological variance in natural systems using remote sensing. These factors are often dominant in the evolution of vegetation cover and the structure of the system (for example, tree and shrub crown sizes and heights, leaf area, density and distribution as well as grass cover patchiness) must be known if the evolution of the system is to be effectively monitored or predicted.

The approach taken by the authors to the interpretation of structure has been through *scene* and *image* modelling, where the scene model represents the target of remote sensing (eg the earth's surface) and the image model includes the effects of imaging or measurement which

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produce the remotely sensed data. The modelling has had three identifiable components of which one represents a combination of the others. The first component was the Li-Strahler inversion model which was developed as a means to derive tree size from remotely sensed data. Its basic premise is that the sizes of the objects (trees) in a discrete canopy affect the pixel to pixel variance in a way that can be measured by image processing and (under suitable conditions) may allow the object sizes to be derived (inverted) from the image spatial variance.

The second component consists of a set of models (called Geometrical Optical, or GO, models) for the changes observed in scene reflectance as the view and sun direction change (Jupp *et al.*, 1986; Strahler and Jupp, 1990; Li and Strahler, 1991). These differences are expressed in the Bidirectional Reflectance Distribution Function (BRDF) and are particularly noticeable when the view direction and the sun direction coincide. At this position (when the observer is looking into where the `shadow' of the platform would be) there is a very bright area or `hotspot' which occurs as the observer senses little or no shadow. The opportunity these models provide for our work is that the BRDF and the scene hotspot function contain significant information relating to canopy structure that scales up in a way that makes it useful for measurements from aircraft and satellite platforms.

Thirdly, we have also been investigating the way image variance and covariance change as scale changes and how much information the covariance data from the image provides about the underlying scene being imaged. This work uses the tools relating scene and image models and scale described in Jupp *et al.* (1988, 1989). This modelling component has recently included an innovative idea based on the fact that not only the image brightness (and colour) change with the relative view and sun positions but also the image variance and covariance (Jupp and Woodcock, 1992). The change in variance with view has been observed empirically, but the work described here provides an ability to model this `BRVF' (Bidirectional Reflectance Variance Function) and assess its value for determining the land surface structure. The work represents an integration of the opportunities provided by the BRDF and the local image variance as a means to define the structure of the land surface.

SIMPLE MODELS FOR SCENES AND IMAGES OF FORESTS AND WOODLANDS

The GO (or hotspot) model for scenes which describe open forest or woodland areas is based on the one described in Strahler and Jupp (1991) and Li and Strahler (1991). In this model, there are four kinds of ground cover `visible' from a given direction. These are referred to as scene components and consist of sunlit canopy (symbol C), shaded canopy (T), sunlit background (G), and shaded background (Z). Each component is assumed to have a characteristic radiance and the radiance of a pixel is modelled as the area weighted combination (or linear mixture) of the characteristic component radiances. That is, the observed radiance of a single pixel (r_S) is modelled as:

$$r_S = k_C R_C + k_T R_T + k_G R_G + k_Z R_Z$$

where C, T, G, and Z indicate the radiances of the four components as named above, R_X represents the (mean) radiance of component `x' and k indicates the sensed proportion of each component within the pixel from the given view direction.

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The mean radiance over the scene (R_S), assuming the view and sun directions are constant, can be written as:

$$R_s = K_C R_C + K_T R_T + K_G R_G + K_Z R_Z$$

where, capital K_X represents the mean or expected value of the varying proportions k_X over the scene. This mean value, as a function of sun and observer position, defines the BRDF of the scene.

In order for the scene BRDF model to be computed, a description of the size and shapes of the objects, their density and how they are distributed over the background is needed and the geometrical relationships between the objects and the expected values of the four components must be established. Jupp *et al.* (1986), Strahler and Jupp (1990) and Li and Strahler (1991) describe such a model for spheroids which is valid for any view or illumination angles using the `Boolean' model of Serra (1982). In the Boolean model, the object `centres' are assumed to be randomly distributed in a `Poisson' distribution. By defining the geometry and the distributions, expressions for the K_X may be derived. Strahler and Jupp (1990) use a simple model for spheroids which is adequate for moderate sun and view zenith angles and Li and Strahler (1991) provide some more general alternative models for resolving the K_X. These basic spheroid scene BRDF models are quite simple and are easily implemented in a spreadsheet.

In the woodlands and open forest areas typical of the area of Australia where the model studies are being made, the pixel to pixel behaviour of the image is quite well described by a simpler form of the model in which the shaded background, sunlit (but still relatively dark) tree and shaded tree components are combined into one so that:

$$r_s = R_X + k_G(R_G - R_X)$$

where X is a composite component combining sunlit and shaded tree and shaded background. This simpler model has the advantage that it shows clearly how, in many woodlands, the image pixel to pixel variation is driven primarily by the variation in the proportion of sunlit background which is visible in the pixels and the contrast between this sunlit background and the other components. It also provides a simple estimate for k_G from images where R_G and R_X are known for an appropriate image channel as:

$$k_G = \frac{R_s - R_X}{R_G - R_X}$$

For such a model, the mean radiance (ie BRDF) over all pixels in a patch with the same basic underlying type of cover and structure is therefore:

$$E(r_s) = R_s = R_X + (R_G - R_X)K_G$$

where K_G is the mean value of k_G, or the expected proportion of visible sunlit background. Moreover, the variance of the pixel radiance is:

$$\mathrm{var}(r_s) = (R_G - R_X)^2 \,\mathrm{var}(k_G)$$

from which it is clear that variance of a scene, for which this simplified form of the model is appropriate, is defined by that of k_G and the contrast between the sunlit background and the composite of tree and shadow.

In the simplified model, the viewed *scene* consists of objects made up of a composite of projected tree plus shadow silhouettes scattered over a sunlit background. The sensor integrates the radiance over a pixel so the model for the resulting *image* is one of objects on a contrasting background regularised by the integration into pixels. Such models may be handled by the tools described in Jupp *et al.* (1988, 1989) from which expressions for the way *var(k_G)* changes with pixel size can be derived. In general, the expressions are quite complex and must be computed numerically.

LI-STRAHLER INVERSION FOR CANOPY STRUCTURE

The Li-Strahler inversion model (Strahler and Li, 1981; Li and Strahler, 1985) was developed by establishing a formula for the variance of a statistic `*m*', which measures the crown cover and is closely related to k_G. If the mean of *m* is denoted *M* and its variance is denoted *V(m)* and if the trees are circular in shape with lognormal size distribution, characterised by the coefficient of variation $C^2_{r^2}$, it follows from that work that the mean radius of the crowns may be found from the formula:

$$\overline{R^2} = \frac{V(m)}{(1+C^2_{r^2})M}$$

The use of this formula depends on how well the measure *m* can be derived from field or image data. The four component and simplified models described above provide one way to estimate *m* from image data.

The applicability of this model for Australian conditions was tested on woodland vegetation at Goonoo State Forest in N.S.W. and Black Mountain in the A.C.T. Canopy reflectance models that use variance methods operate as a function of the size and spacing of objects on the ground and the pixel resolution of the sensor. These models were used to invert image data at different spatial resolutions to provide maps representing the cover percent and crown size of vegetation. To validate model results, cover percent and crown size data were compared to equivalent data collected in the field. The results, though promising, showed a high degree of variability due to factors either poorly modelled or not included in the analysis. Thus, image inversion results were not accurate enough to provide absolute values of vegetation structure. However, the cover percent and crown size maps provide good relative estimates of structural changes and with continued research, indicate the utility of such maps as a resource management tool.

THE CANOPY BRDF AS A MEASURE OF CANOPY STRUCTURE

The canopy BRDF and the associated hotspot effect have been the subject of much study as the behaviour of the data near the hotspot is related to combinations of the height, size and shape of the objects (in this case the trees) which are creating the texture of the surface. The simple model described in this paper naturally describes the hotspot effect as the point where the sun and observer `shadows' totally coincide and it has been used to demonstrate very significant scaling properties of the hotspot. While there have been many attempts to model the hotspot effect with semi-empirical models, the models described in Jupp *et al.* (1986) and Strahler and Jupp (1990) were the first to use models that could be related directly to canopy structure and make clear the fundamental scaling properties of the hotspot effect. These methods have since been used to derive models for the hotspot effect in crop canopies in which the nature of the hotspot variation is related directly to leaf size and shape (Jupp and Strahler, 1991; Qin, 1993).

Initial investigations of the BRDF of Australian open forest areas over the Goonoo test site were made using wide angle aerial photography and reported in Jupp and Woodcock (1992). The photography allowed a wide range of look angles to be measured and, by stacking frames along runs of overlapping photography, the mean BRDF could be estimated. However, it was found that a large number of photographs are needed to reduce the variance in the highly variable Goonoo test area. Therefore, in January 1993, we used a Daedalus 1268 scanner (DATM) to fly the test area at a number of heights and specifically into, and at 90° to the sun's Principal Plane. The averaging of up to 1000 scanlines enabled very stable estimates for the BRDF to be obtained in these two planes of the view hemisphere. Figure 1 shows the result of one such run using Band 9 (the shortwave infrared) of the DATM. The model estimate plotted has used structural information from field investigations but the radiances of the components have been estimated to optimise the fit to the data.

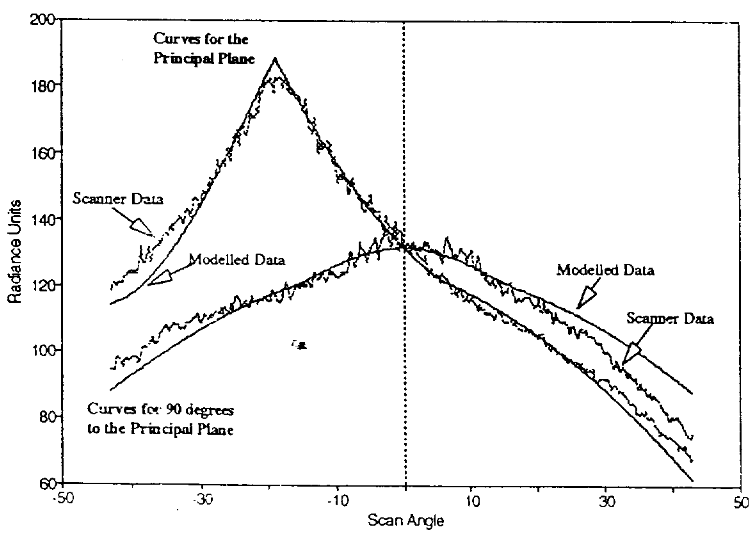

Figure 1: BRDF (for SWIR) along the Principal Plane and 90 degrees to Principal Plane - modelled data compared to DATM scanner data.

Due to a lack of information on the calibration of the DATM channels, the study was based on the SWIR and the thermal infrared channels where the atmospheric effect was small. There, the variation could be modelled very well by the simple four component BRDF model. However, it was found that cover and the component radiances had a redundancy in them in that if the cover was changed the same fit to the data could be obtained by adjusting the component radiances. If the component radiances are known, however, both cover and the main structure factors consisting of ratios of tree height to diameter and diameter to thickness were well resolved by the BRDF in the two principal planes. Moreover, even when cover and `colour' are not resolved, the main structure ratios are very well established in the data. Figure 2 shows the same data as Figure 1 but with models plotted with varying ratios of tree height to crown diameter. The component radiances have been re-adjusted to optimise the fit. There is quite clear and accurate structural information in the BRDF - especially near the hotspot region.

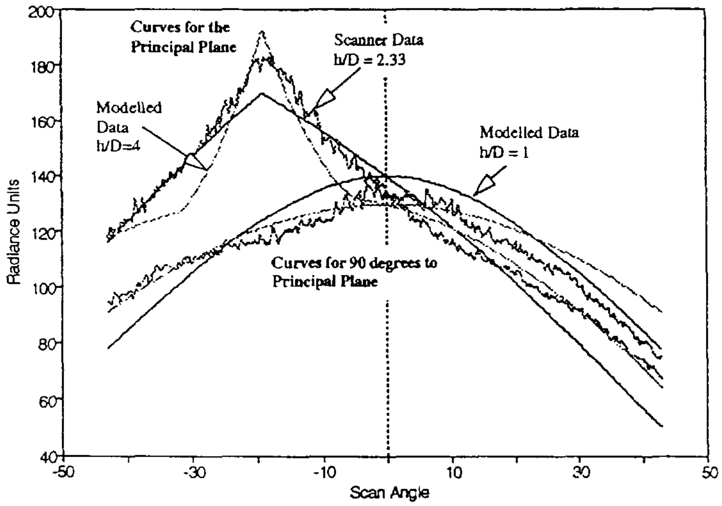

Figure 2: BRDF (for SWIR) along principal plane and 90 degrees to principal plane - modelled data (with variable structure ratios) compared to DATM scanner data.

The BRDF and hotspot variations are well known effects in aerial photography and airborne scanner data. Even current satellite images with wide angular swath show considerable variation due to the surface BRDF. In the face of this variation, people have often tried to `correct' for the effect by adjusting image brightness data as a function of the relative sun and view directions. Ultimately, such methods are of limited use since, as our discussion shows, the effect is not really one of varying brightness but rather one of varying proportions of cover components. Methods which adjust overall brightness therefore artificially modify component colours to `compensate' for these changing proportions. Nevertheless, there is considerable value in using simple models with a few parameters to describe the BRDF. If images need to be modified for (say) mosaicing, an adjustment based on a BRDF model may be quite useful. We have been investigating some of the alternatives that have been developed in recent times (see Liang and Strahler, 1994) against the base of the Goonoo data and will present a summary of the findings at the Conference.

INVESTIGATING THE CANOPY BRVF

Even for a scene with a consistent underlying BRDF, the pixel data change significantly with view position and the variance (also the spatial covariance) changes with both view angle and pixel size. Even a uniform area of forest cover will therefore create significant variation in photography, airborne scanner data and satellite images with widely varying view directions. The variation in the mean - or BRDF - in a scene was discussed by Jupp and Woodcock (1992) and called the scene `BRVF' or Bidirectional Reflectance Variance Function. The observed BRVF functions for the aerial photography and the DATM data for varying altitudes (and therefore pixel sizes) have been established and show a consistent view angle dependent variation. Although a model for the BRVF has been established, this is still a research area and only preliminary results will be described.

The main opportunity presented by a study of the BRVF is that it integrates the two current approaches to inversion of forest structure as represented by the Li-Strahler inversion method and the various methods of inverting the BRDF. That is, the Li-Strahler inversion uses the image mean and variance to estimate tree size through the way it affects the pixel to pixel variation in the image. The BRDF, on the other hand, takes no account of the pixel to pixel variation (it is a nuisance in most cases) but uses the way the average scene radiance changes with sun and view angles to infer structure. The greatest problem faced by the Li-Strahler inversion is the sensitivity of the result to an accurate knowledge of the component radiances. The result of errors in these components is worst for tree size estimation, however cover can often be very well estimated. In the BRDF inversion, cover and component radiance are redundant but some significant structure parameters are well resolved. There is a level of complementarity in these `blind' spots which makes their combination into BRDF/BRVF modelling an important research direction.

CONCLUSIONS

Using mean, variance and angular variations (the BRDF and BRVF) derived from multi-sun and observer angle sensing of the earth offers the possibility of monitoring structural changes at a finer grain than image resolution within broad mosaics of different covers. Data of this type are currently available from aerial photography, airborne video systems and airborne scanners (such as the DATM, CASI and ASAS). The results obtained to date are also useful for interpreting AVHRR data. In the future, MISR and POLDER on the EOS platform will enable space data to be analysed using all three types of measurement. In particular, the hotspot model, with its scaling properties, offers new opportunities to monitor land surface structure from space. Unlike much currently operational image processing, however, its complete exploitation depends on achieving a balance between empirical study and physical modelling.

Models for the resulting two primary directional statistics of images - the Bidirectional Reflectance Distribution Function (BRDF) and the Bidirectional Reflectance Variance Function (BRVF) have been tested using low altitude, wide angle photography and airborne scanner data from an Australian open forest area. The conclusion is that the models can explain the angular variation and that the variation in radiance in remotely sensed images and its spatial variance and scaling effects, which are created by the combination of land surface structure, the sun position and view angle, do provide a significant opportunity for detecting temporal changes in woodland and open forest cover and structure. While the original form of the Li-Strahler inversion model has proved difficult to make operational, it has the ability to separate land surfaces into structural types and, combined with the more recent BRDF models, may re-emerge with greater resolving power from our developments of the BRVF.

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